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Worldwide Harmonized Heavy Duty Emissions Certification Procedure

Exhaust Emissions Measurement
ISO 2nd Interim Report

ECE-GRPE WHDC Subgroup "ISO Activities"

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Test Institutes: EMPA, JARI, RWTUEV, SwRI

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Bienvenue
dans le 3ième millénaire

SECOND INTERIM REPORT

WHDC-SUBGROUP "ISO ACTIVITIES" (IA)
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PRELIMINARY RESULTS OF THE ISO CORRELATION STUDIES

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0 SUMMARY

Four correlation studies were conducted in the framework of the ISO/TC 22/SC 5/WG 2 work program mandated by the WHDC group. The studies were devoted to determining

- the correlation between partial flow dilution and full flow CVS systems for particulate matter (PM);
- the correlation between raw and dilute (CVS) measurement of the gaseous emissions components HC, CO and NO_x.

With regard to PM, the following results have been achieved, so far:

- Overall, partial flow dilution systems measured slightly lower (2% to 15% on average) PM than CVS systems on steady state and transient cycles;
- at the EMPA study, the differences were mainly statistically non significant;
- at the JARI and RWTUEV studies, the differences were greater and mostly statistically significant;
- at the SwRI study, the correlation was very poor compared to the above studies and to current knowledge;
- any conclusions from the SwRI correlation study are only possible after further analysis;
- when using aftertreatment systems, partial flow dilution systems measured slightly higher PM;
- the transient control capability of partial flow dilution systems was proven in all correlation studies;
- PM measurement accuracy was good down to PM levels of 0.015 g/kWh, if PM is mainly carbonaceous, and significantly deteriorated, if the main portion is SOF and/or sulfate; this problem especially occured with aftertreatment systems and can only be avoided by using sulfur free fuel.

With regard to gaseous emissions, the following results have been achieved, so far:

- In general, the difference between raw and dilute (CVS) measurement was within ± 5%;
- the influence of different calculation algorithms for the raw measurement was minor within ± 3%;
- the transient measurement capability of current measurement systems was proven in all correlation studies;
- therefore, raw gaseous emissions measurement should be allowed for transient cycles.

It should be noted that this report is preliminary, only. A more detailed analysis including extensive statistical evaluation will be contained in the final report, which will be submitted by May 2001.

1 INTRODUCTION

In order to protect the health of society, government agencies impose environmental regulations on mobile sources by setting limit values for the gaseous and particulate pollutants emitted by the vehicle. For heavy duty engines, the limit values are generally expressed in terms of emissions produced by the engine on a certain test cycle. Differences in environmental regulations between different countries and world markets have resulted in variations in engine design, and can be said to represent barriers to the distribution of environmentally friendly products across international borders.

Since harmonization of engine environmental regulations could remove these barriers, the GRPE mandated, at its 33rd session from 13-15 January 1997, the WHDC subgroup, chaired by Dr. Havenith of the Dutch Ministry of Environment (VROM), with the task of developing a harmonized heavy duty certification procedure. Within this group, two subgroups have been established in order to manage and coordinate the research programs necessary for fulfilling the task:

- the subgroup "Fundamental Elements" (FE) which deals with the creation of a new test cycle and strategies to combat cycle by-pass; this task will be conducted by independent research institutes (TÜV, TNO, JARI);
- the subgroup "ISO Activities" (IA) which deals with the interim steps of harmonization where elements of existing legislation will be improved where appropriate; this task has been entrusted to ISO TC 22/SC 5.

This second interim report describes the tasks and objectives of the ISO activities on emission measurement procedures, and the results of the different correlation studies conducted by independent laboratories, available so far.

2 EXHAUST EMISSIONS MEASUREMENT

2.1 Task and Objectives

The task of the ISO work program is to develop a cost effective and accurate exhaust emissions measurement procedure for gaseous and particulate pollutants under transient and steady state engine operation that can be the basis of a harmonized heavy duty certification procedure.

The objectives of the work are the development of an ISO standard on the measurement of exhaust emissions under transient conditions, and the management of four correlation studies on different measurement procedures. The work is focused on partial flow dilution and raw exhaust measurement for use on transient test cycles as an alternative to the currently required full flow dilution (CVS) systems.

Today, partial flow dilution for particulates (PM) and raw exhaust measurement for the gaseous components (CO, HC, NO_x) are only allowed for steady state cycles. Since they are less expensive and considerably less spacious than full flow dilution systems, their introduction for transient cycles is of prime interest to the engine industry as well as to the type approval authorities.

2.2 Terms of Reference

At the beginning of the test program, the terms of reference were determined and approved by the WHDC working group. They are listed below:

- Analysis of current and alternative measurement procedures
  - Accuracy of current measurement procedures as regards future low emitting engines
  - Evaluation of multi-component systems for gaseous exhaust components
- Analysis of flow compensation systems for transient engine operation
  - Evaluation of direct exhaust gas flow sensors and/or tracer methods
  - Evaluation of fast mass flow sensors for proportional sample control
  - Development of calculation procedure
- Correlation study
  - Analysis of existing round robin data
  - Correlation between partial and full flow systems for PM emission
  - Correlation between raw and diluted measurement for gaseous emissions
- Development of an ISO standard

2.3 Correlation Studies

External research work was contracted out for the principal investigations and the correlation study. In total, four correlation studies were conducted whose results have been used in establishing the ISO standard. Whereas for the gaseous emissions measurement the major emphasis was put on developing algorithms for calculating the emissions values, some basic parameters were investigated in the PM correlation studies that can influence PM mass and composition.

Those parameters are separated into those which are essential for both partial flow and full flow dilution systems:

- Dilution ratio: 4, 6, 8, 12
- Filter face velocity: 30, 50, 65 (100) cm/s
- Sample filter loading: 0.25, 0.5, 1.0 mg

and those which apply to partial flow dilution systems, only:

- Sample line temperature: 150 °C, 200 °C
- Sample line diameter: 4, 10 mm
- Sample line length: 0.0, 0.5, 1.5 m

- Tunnel heating: w/o, 50 °C
- Sample probe design: open, multihole, reversed, hatted

Since those parameters are known to have an influence on the PM measurement result, they must be specified in the ISO standard. In order to cover a wide range of measurement systems and engine technology, the correlation studies were carried out at different laboratories, as shown in the following table. Correlation studies I and III were funded by OICA, correlation study II jointly by Japanese MOT and JAMA, and correlation study IV jointly by US EPA and EMA.

TIME	SUBJECT	DONE BY	BUDGET [Euro]
04/1998 - 10/1998	Analysis of Exhaust Measurement Systems	AVL; Horiba	
04/1998 - 05/1999	Establishment of Future Accuracy Requirements	Convener; WG 2	
06/1998 - 02/1999	Analysis of Exhaust Flow Measurement (Air + Fuel / Tracer Method)	Iveco; JARI; Horiba	
10/1998 - 02/2000	Analysis of ACEA Round Robin Data	ACEA EXP-EMT	
01/1999 - 12/1999	Development of Calculation Procedures	Convener; MTC	
02/1999 - 05/1999	Correlation Study I (PM Partial and Full Flow Systems; Gaseous Emissions Raw vs. Dilute Measurement)	EMPA (1 eng./3 instr.)	155.000
07/1999 - 11/1999	Correlation Study II (PM Partial and Full Flow Systems; Gaseous Emissions Raw vs. Dilute Measurement)	JARI (1 eng./1 instr.)	--------- funded by JAMA and MOT
12/1999 - 09/2000	Correlation Study III (PM Partial and Full Flow Systems; Gaseous Emissions Raw vs. Dilute Measurement)	RWTÜV (1 eng./2 instr.)	125.000
07/2000 - 03/2001	USA Correlation Study (Add-on to EPA/CARB program on nonroad engines)	SwRI (4 eng./2 instr.)	--------- funded by CARB, EPA, EMA
03/2001	End of WG 2 Technical Work Program	WG 2	
08/2000	Submission of Committee Draft Circulation of DIS After SC 5 Approval	SC 5 Secretariat	
	Total Budget for OICA		**280.000**
01/2003 - 05/2004	System Verification Through Round Robin Testing	Technical Service; Engine Industry	

***Table 1**: Timetable of exhaust emissions measurement work program*

3 RESULTS OF THE EMPA CORRELATION STUDY

The first correlation study was contracted to the Swiss test laboratory EMPA and started at the beginning of February 1999 with the Mercedes OM 501 LA engine (12 l, V6, TCI, Unit Pump, 260 kW) and two partial flow systems from AVL and Control Sistem. The Pierburg system was investigated in the system correlation exercise, only, but not in the parameter study. A city diesel fuel with 20 ppm sulfur level, low density (820 kg/m³) and high cetane number (56) was used in order to reduce the particulate level of the engine to 0.04 g/kWh on the ESC cycle and to 0.07 g/kWh on the ETC cycle.

3.1 Transient Operation of Partial Flow Dilution Systems

Three particulate measuring units were run in parallel: a state of the art CVS full flow system as reference system and two partial flow systems provided by AVL (Smart Sampler SPC 472) and by Control Sistem (PSS-20). Their transient capability was checked by comparing the sample flow rate to the exhaust flow rate. The two traces must coincide very closely in order to enable proportional sampling. Figure 1 shows for the PSS 20 that this condition was met during a portion of the European Transient Cycle (ETC).

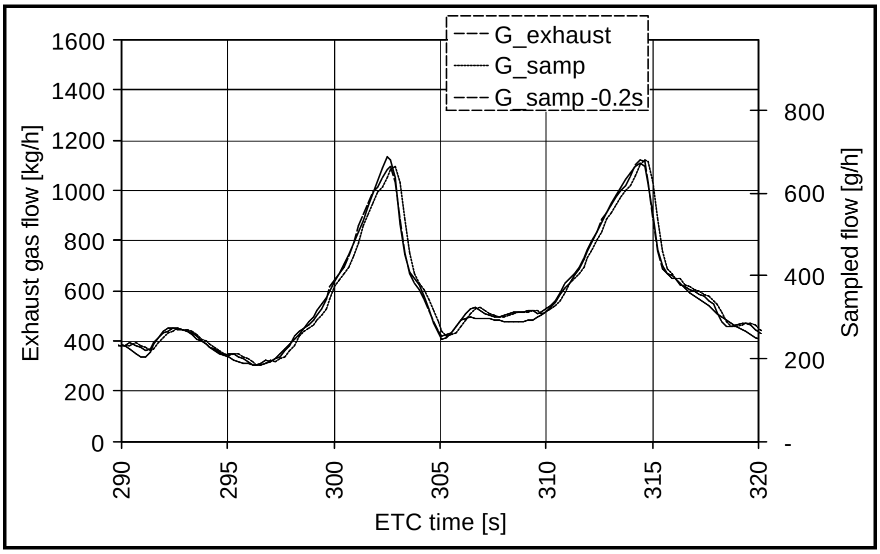

***Figure 1**: Transient sampling during the ETC (Control Sistem PSS-20)*

For the complete cycle, the proportionality was proven by a linear regression between sample probe flow (g/h) and exhaust flow (kg/h) signals. Table 2 shows that both systems have a very good response to changes of the exhaust flow.

Regression data	AVL	Control Sistem
SE (% of max.)	2.71...4.08	2.49
Slope r	0.62...0.93	0.60
Correlation Coefficient R²	0.94...0.99	0.97
Y intercept [g/sec]	-0.002...0.002	0.0024

Table 2: *Regression analysis between sample probe and exhaust gas flow on the ETC cycle*

3.2 Parameter Study

a. Pretests

Pretests were carried out in order to determine, whether the muffler or the connection of the CVS full flow system had an influence on the measuring results. Also, it was verified, that both partial flow systems were operating well together and did not influence each other. The results can be summarized, as follows:

- Without the muffler installed, the PM level slightly increased
- The operation of the CVS system did not influence the measurement results of the partial flow system

b. Dilution Ratio

To check the influence of the dilution ratio on the particulate mass and composition, it was varied with each system between 4 and 12. For the test cycles, the adjustments of the parameters were made with the ESC mode C100.

Because it was not possible to control the dilution air temperature and humidity of all systems, the preconditionning of the dilution air was kept constant during these tests. This means, that the filter temperature changed with the dilution ratio. These two important factors could not be considered isolatedly in this program.

Figures 2 and 3 show, that no trend of the PM level over a dilution ratio between 4 and 12 could be observed with either system.

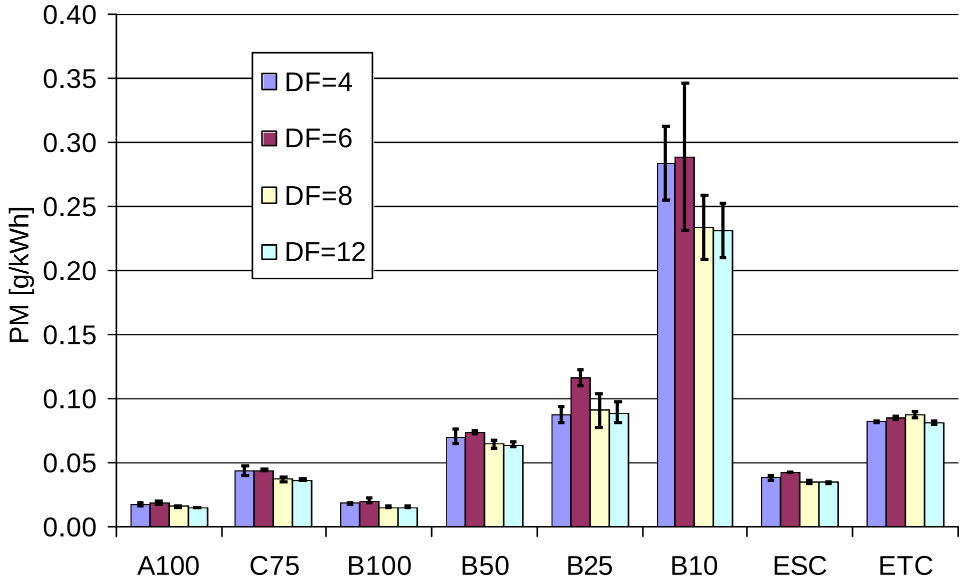

Figure 2: *Influence of dilution ratio for the AVL system*

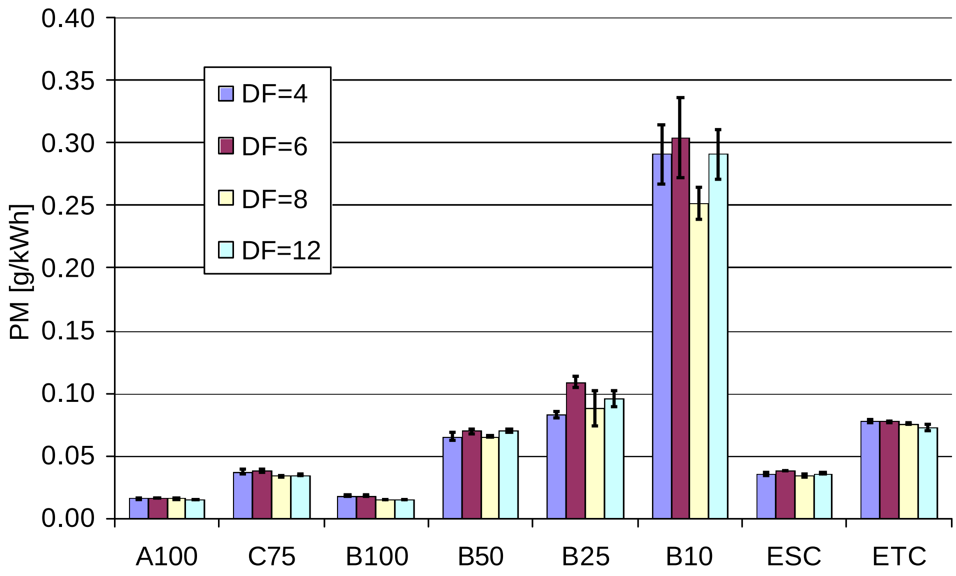

Figure 3: *Influence of dilution ratio for the CVS full flow system*

c. Filter Face Velocity

The range of the adjustable filter face velocity differed from system to system. The AVL system e.g. allowed only total mass flows below 2 g/s, which was equivalent to 61 cm/s filter face velocity. With the other partial flow system (Control Sistem), velocities of 100 cm/s and more were possible. This was the reason, why for every system the maximum possible setting had been chosen for the measurements with the high filter face velocity.

Figure 4 shows that no trend of the PM level over a filter face velocity between 30 and 100 cm/s was observed with the CS system that had the greatest spread of filter face velocity.

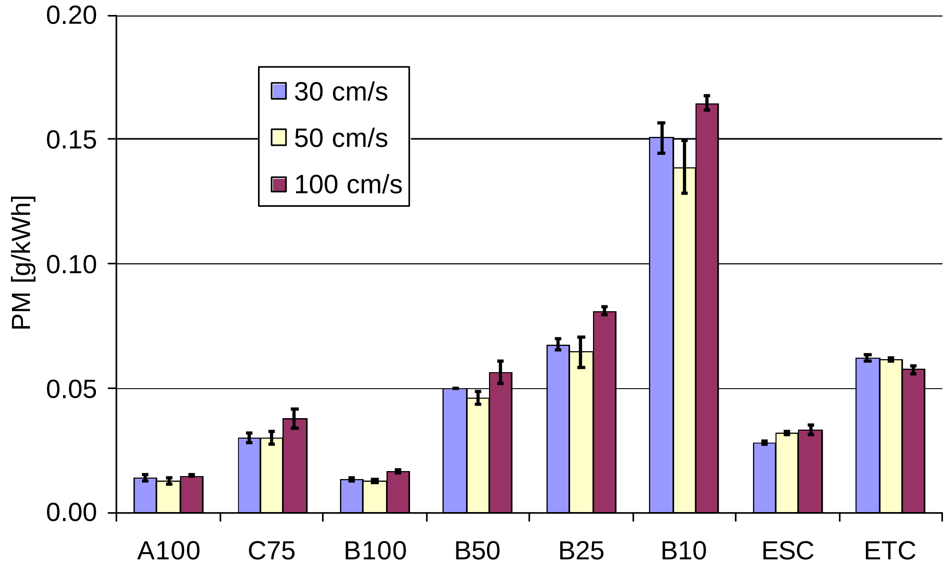

***Figure 4**: Variation of the filter face velocity with the Control Sistem unit*

d. Sample Filter Loading

The minimum recommended filter loading in the current EURO III regulation is 1.3 mg for filters with a 70 mm diameter. With the engine used in this program, the filter loading in the European steady state cycle (ESC) was about 0.7 mg at reference conditions.

To avoid expensive repetitions of the cycle, the minimum recommended filter loading has to be lowered or the exhaust gas flow over the filter has to be increased.

To detect the influence of the filter loading on the measuring results, the loading was lowered down to 0.25 mg, which was only about 12 times higher than the minimum required standard deviation of the microbalance used for weighing the particulate filters.

Figure 5 shows that the PM level was not influenced by varying the filter loading between 0.25 and 1 mg.

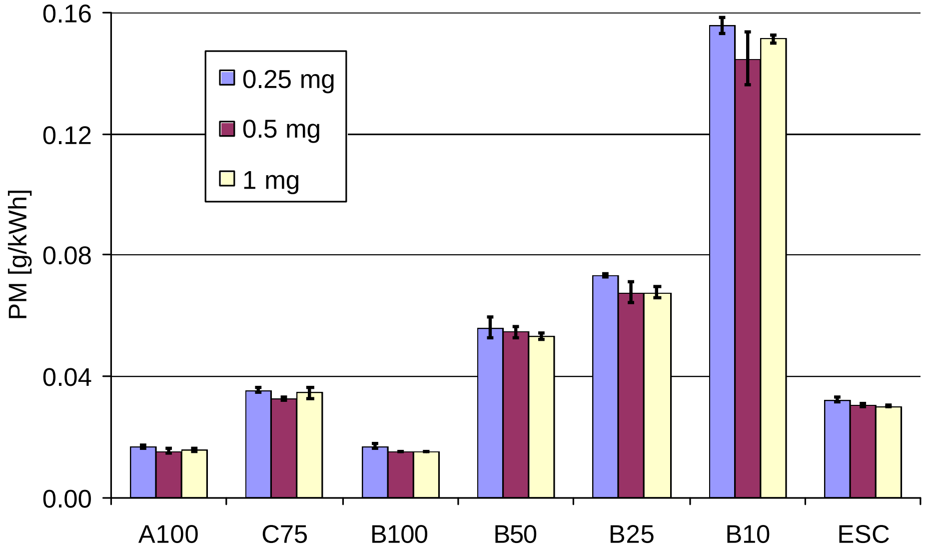

***Figure 5**: Influence of the filter loading (Control Sistem)*

e. Sample Line Temperature

The temperature in the mixing zone between exhaust gas and dilution air is generally considered to be of high importance for particulate formation and measurement. The sample line heating influenced this temperature, since the tunnel inlet temperature was observed to be higher with the higher sample line temperature.

Figure 6 demonstrates that the CS system measured higher values on both test cycles with the higher sample line temperature, but overall no clear trend was observed.

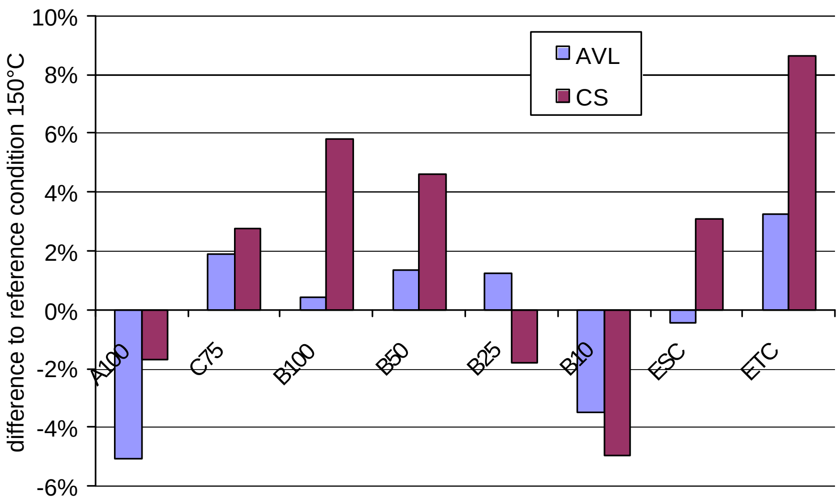

***Figure 6**: Sample line heating (partial flow systems)*

f. Tunnel Heating 50 °C

Tunnel heating caused a significant increase of the filter face temperature and therefore resulted in a slight decrease of the SOF content. As shown in figure 7, a lower PM level at mode B 10 was observed, but a higher PM level on the ETC. On the other modes and the ESC, the influence was minor.

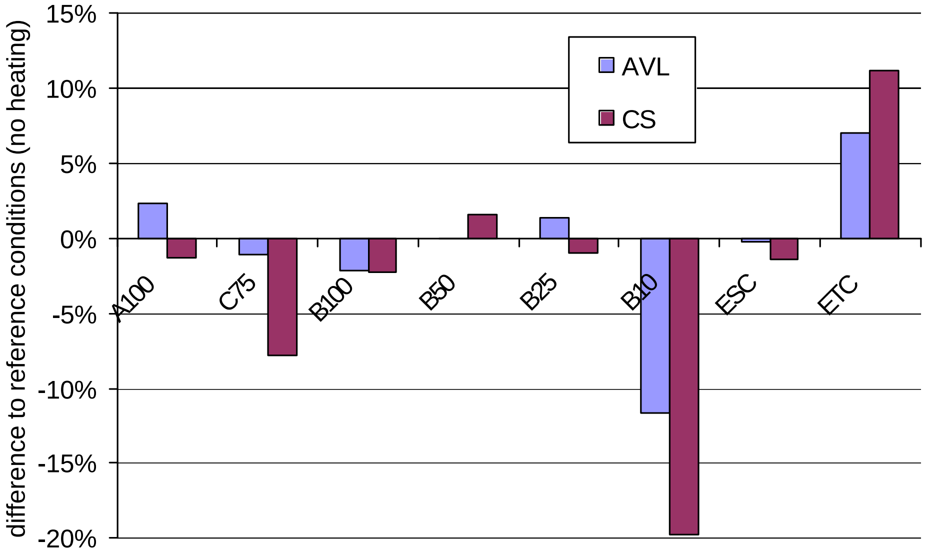

***Figure 7**: Influence of the tunnel heating (partial flow systems)*

g. Sample Line Length

Generally, the temperature level decreased with the longer sample line. With the shortest line, all partial flow systems exceeded the filter face temperature limit (52°C) in some of the single modes. The measuring results of the CS system demonstrated a slight trend on the test cycles to lower particulate emissions with longer sample lines. But in some single modes, an opposite trend could be observed (see figure 8). The AVL system did not indicate a clear trend.

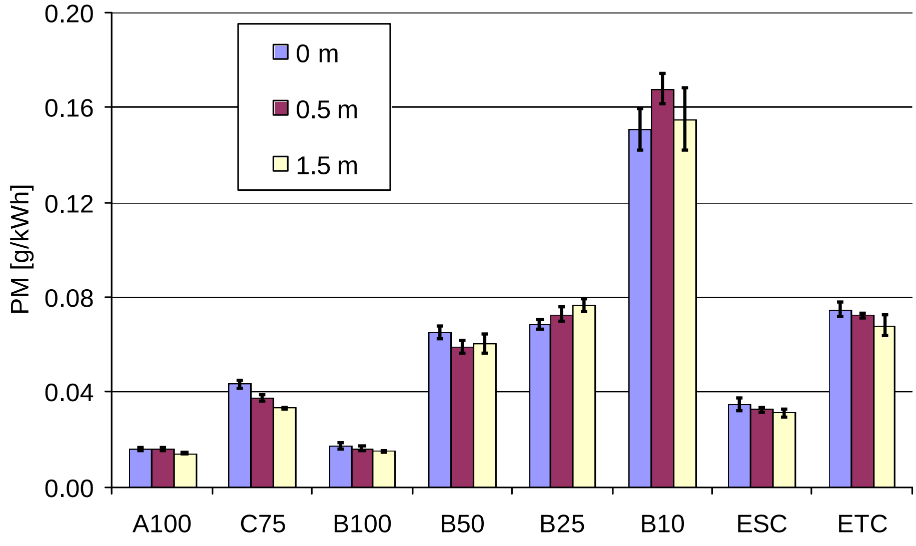

***Figure 8**: Influence of the sample line length (Control Sistem)*

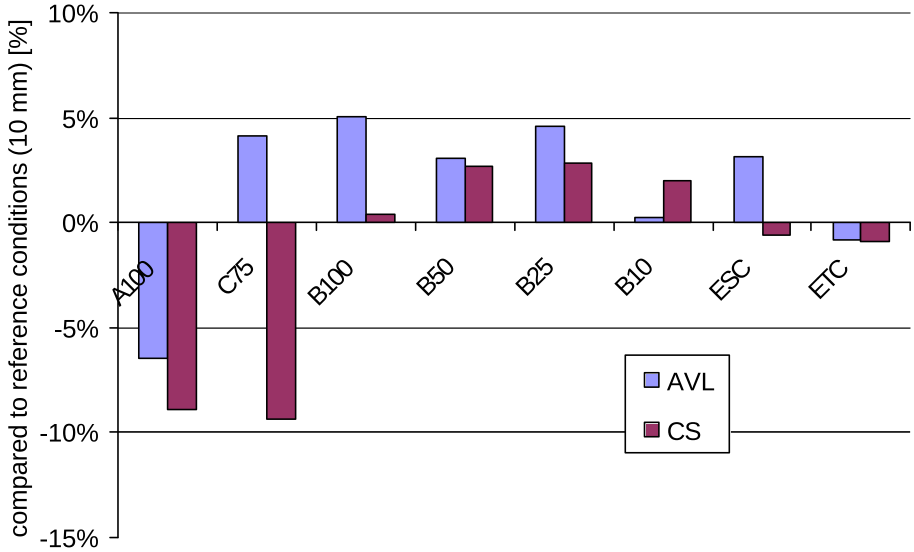

***Figure 9**: Influence of the sample line diameter*

h. Sample Line Diameter

When the sample line diameter was reduced from 10 mm to 4 mm, the velocity of the exhaust gas in the line was six times higher than before. Figure 9 shows that the results with the smaller diameter of 4 mm were within 5 % except for modes A 100 and C 75. It can therefore be concluded that there is no trend of the PM level at diameters of 4 and 10 mm.

3.3 Statistical Validation

Since most of the influences reported above were only minor, a statistical validation was carried out in order to determine their significance. In a first step, the difference between the three systems over all parameters investigated was evaluated by a t-test for each test mode and cycle. This test compares the mean values of the three systems on each individual test series against each other for significant differences. A significant difference is indicated by a t-test value > 95 %. The results are summarized in table 3. The t-test comparison shows that except for mode A 100 there is generally no statistically significant difference between the mean values of the systems. This is especially valid for the ETC transient cycle proving again the transient capability of the partial flow dilution systems. No explanation could be found for the differences observed with mode A 100.

Mode	AVL/CVS	CS/CVS	AVL/CS
A 100	99.17 %	99.98 %	87.88 %
C 75	20.56 %	37.57 %	53.38 %
B 100	41.73 %	81.09 %	54.13 %
ESC	68.01 %	98.64 %	87.01 %
ETC	17.93 %	40.51 %	26.30 %

***Table 3**: T-test comparison between mean values of measurement systems*

In a second step, the influence of the investigated sampling parameters on the PM result was tested by means of an ANOVA (Analysis of Variance). Each parameter and each test mode were analyzed separately in order to allow a more detailed picture. The results are summarized in table 4.

Statistically, the most significant parameter was the dilution ratio. This is not surprising, since it has been known that the dilution ratio can influence the soluble organic fraction of the particulates and thus the total particulate mass. However, in this study no influence was observed at mode B 10 with the highest SOF. In addition, an overall PM maximum value was observed at a dilution ratio of 6 and lower PM values at lower and higher dilution ratios, as shown in figure 2. These results are in contradiction to current knowledge. It is therefore questionable, whether the observed significance can be attributed to the dilution ratio effect only, or whether other effects occurred in this test series.

From the other general parameters, filter face velocity and filter loading showed only very few significant effects. PM levels tended to be slightly higher at low filter face velocity and low filter loading. This finding would allow lower minimum filter loadings in future emissions regulations to take account of the low PM levels of those engines.

For the parameters related to partial flow dilution systems, significant effects were only observed in a few cases, and they were not consistent. PM levels tended to be slightly lower with a longer sample line, so sample lines shorter than 1.5 m are recommended. For sample line temperature, tunnel heating and sample line diameter the current legislative requirements seem to be acceptable.

Parameter	Mode	CVS	AVL	CS	Parameter	Mode	CVS	AVL	CS
Dilution ratio	A 100	-	-		Tunnel heating	A 100		-	-
	C 75	**	**			C 75		-	-
	B 100	**	**			B 100		-	-
	B 50	*	*			B 50		-	-
	B 25	*	*			B 25		-	-
	B 10	-	-			B 10		**	**
	ESC	**	**			ESC		-	-
	ETC	*	**			ETC		**	**
Filter face velocity	A 100	-	-	-	Sample line length	A 100		-	-
	C 75	-	-	*		C 75		*	-
	B 100	-	**	**		B 100		**	-
	B 50	*	*	*		B 50		-	-
	B 25	-	-	-		B 25		-	-
	B 10	-	-	-		B 10		*	-
	ESC	*	-	-		ESC		-	-
	ETC	**	**	**		ETC		-	-
Filter loading	A 100	-	*	-	Sample line diameter	A 100		**	**
	C 75	-	-	-		C 75		-	-
	B 100	-	**	**		B 100		-	-
	B 50	-	-	-		B 50		-	-
	B 25	*	*	-		B 25		-	-
	B 10	-	-	-		B 10		-	-
	ESC	**	**	**		ESC		-	-
	ETC	-	-	-		ETC		-	-
Sample line temperature	A 100		-	-					
	C 75		-	-					
	B 100		-	-					
	B 50		-	-					
	B 25		-	-					
	B 10		-	-					
	ESC		-	-					
	ETC		-	-					

- = non significant; * = significant; ** = highly significant

***Table 4**: ANOVA results of parameter study*

3.4 Correlation Study

The correlation study was conducted on two transient cycles (ETC, US FTP) and two steady state cycles (ESC, Japanese 13-mode cycle) according to the ISO equivalency criterion, i.e. a 7 sample pair comparison between the systems under investigation. The CVS full flow dilution system was used as the reference systems, and the candidate partial flow dilution systems from AVL, Control Sistem (CS) and Pierburg (PBG) compared against it by means of the two-sided Student t-test. This statistical method examines the hypothesis that the population mean value for an emission measured with the candidate system does not differ from the population mean value for that emission measured with the candidate system. The hypothesis was tested on the basis of a 1 % significance level of the "t" value. The test series is shown in table 5. The test series was repeated with the engine equipped with a particulate trap (CRT system) in order to also judge the systems at very low PM levels expected in the future.

Day	Testing Scheme
1	ESC; ESC; ESC; ETC; ETC; ETC
2	FTP; FTP; FTP; JAP; JAP; JAP
3	ETC; ETC; JAP; JAP; FTP: FTP; ESC; ESC
4	JAP; JAP; ESC; ESC; FTP; FTP; ETC; ETC

Table 5: *Testing scheme of correlation study*

The results of the t-test in comparison to the CVS system are shown in table 6 for the AVL, in table 7 for the CS and in table 8 for the PBG. The AVL was equivalent on the ESC and JAP test cycles both with and w/o trap and on the ETC with trap. It measured low on the ETC and FTP w/o trap, but high in the case with trap. The CS was similar with most of the results slightly lower than the CVS when measured w/o trap, but higher when measured with trap. The PBG showed good correlation in all cases except FTP with trap.

The results with the PBG are also shown graphically in figures 10 and 11. The error bars represent the test-to-test repeatability based on two standard deviations. In all cases, there is a significant overlap indicating that the system is equivalent to the CVS system.

Statistical Data	ESC w/o Trap	ESC with Trap	ETC w/o Trap	ETC with Trap	FTP w/o Trap	FTP with Trap	JAP w/o Trap	JAP with Trap
Mean, CVS	0,03090	0,00619	0,06830	0,00437	0,07883	0,00544	0,05343	0,01974
Std. Dev., CVS	0,00065	0,00306	0,00077	0,00126	0,00130	0,00133	0,00319	0,00474
COV, CVS	2,10%	49,49%	1,13%	28,81%	1,65%	24,46%	5,96%	24,00%
Sample Size, CVS	7	7	7	7	7	7	7	7
Mean, AVL	0,03099	0,00761	0,06167	0,00599	0,06904	0,00996	0,05354	0,01721
Std. Dev., AVL	0,00161	0,00240	0,00130	0,00117	0,00230	0,00215	0,00333	0,00176
COV, AVL	5,20%	31,51%	2,11%	19,61%	3,33%	21,59%	6,23%	10,20%
Sample Size, AVL	7	7	7	7	7	7	7	7
Mean Difference	0,00009	0,00143	-0,00663	0,00161	-0,00979	0,00451	0,00011	-0,00253
Relative Difference	0,28%	23,09%	-9,71%	36,93%	-12,41%	82,94%	0,21%	-12,81%
F-Test	0,04341	0,56894	0,22945	0,86908	0,18936	0,26884	0,91601	0,02909
Statistical Conclusion	C>R	C=R	C=R	C=R	C=R	C=R	C=R	C<R
T-Test	0,89935	0,35037	0,00000	0,02891	0,00000	0,00049	0,94880	0,22388
Statistical Conclusion	C=R	C=R	C<R	C=R	C<R	C>R	C=R	C=R

***Table 6**: Correlation results of the AVL system*

Statistical Data	ESC w/o Trap	ESC with Trap	ETC w/o Trap	ETC with Trap	FTP w/o Trap	FTP with Trap	JAP w/o Trap	JAP with Trap
Mean, CVS	0,03090	0,00619	0,06830	0,00437	0,07883	0,00544	0,05343	0,01974
Std. Dev., CVS	0,00065	0,00306	0,00077	0,00126	0,00130	0,00133	0,00319	0,00474
COV, CVS	2,10%	49,49%	1,13%	28,81%	1,65%	24,46%	5,96%	24,00%
Sample Size, CVS	7	7	7	7	7	7	7	7
Mean, CS	0,03346	0,00887	0,05883	0,00763	0,06617	0,01223	0,04463	0,01668
Std. Dev., CS	0,00284	0,00190	0,00388	0,00101	0,00375	0,00072	0,00331	0,00118
COV, CS	8,50%	21,42%	6,59%	13,21%	5,66%	5,89%	7,41%	7,10%
Sample Size, CS	7	7	7	7	7	7	7	6
Mean Difference	0,00256	0,00269	-0,00947	0,00326	-0,01266	0,00679	-0,00880	-0,00306
Relative Difference	8,28%	43,42%	-13,87%	74,51%	-16,06%	124,67%	-16,47%	-15,50%
F-Test	0,00224	0,27098	0,00103	0,60213	0,02078	0,16054	0,93101	0,00797
Statistical Conclusion	C>R	C=R	C>R	C=R	C>R	C=R	C=R	C<R
T-Test	0,05544	0,07210	0,00053	0,00018	0,00005	0,00000	0,00028	0,14393
Statistical Conclusion	C=R	C=R	C<R	C>R	C<R	C>R	C<R	C=R

***Table 7**: Correlation results of the CS system*

Statistical Data	ESC w/o Trap	ESC with Trap	ETC w/o Trap	ETC with Trap	FTP w/o Trap	FTP with Trap	JAP w/o Trap	JAP with Trap
Mean, CVS	0,03090	0,00619	0,06830	0,00437	0,07883	0,00544	0,05343	0,01974
Std. Dev., CVS	0,00065	0,00306	0,00077	0,00126	0,00130	0,00133	0,00319	0,00474
COV, CVS	2,10%	49,49%	1,13%	28,81%	1,65%	24,46%	5,96%	24,00%
Sample Size, CVS	7	7	7	7	7	7	7	7
Mean, PBG	0,03313	0,00921	0,06478	0,00539	0,07933	0,00877	0,05004	0,01944
Std. Dev., PBG	0,00716	0,00236	0,00388	0,00080	0,00360	0,00068	0,00398	0,00523
COV, PBG	21,60%	25,65%	5,98%	14,87%	4,54%	7,78%	7,96%	26,90%
Sample Size, PBG	7	7	6	7	7	7	7	7
Mean Difference	0,00223	0,00303	-0,00352	0,00101	0,00050	0,00333	-0,00339	-0,00030
Relative Difference	7,21%	48,96%	-5,15%	23,20%	0,63%	61,15%	-6,34%	-1,52%
F-Test	0,00001	0,54518	0,00116	0,29516	0,02534	0,12856	0,60172	0,81661
Statistical Conclusion	C>R	C=R	C>R	C=R	C>R	C=R	C=R	C=R
T-Test	0,44283	0,06048	0,07704	0,09733	0,73904	0,00007	0,10453	0,91231
Statistical Conclusion	C=R	C=R	C=R	C=R	C=R	C>R	C=R	C=R

***Table 8**: Correlation results of the Pierburg system*

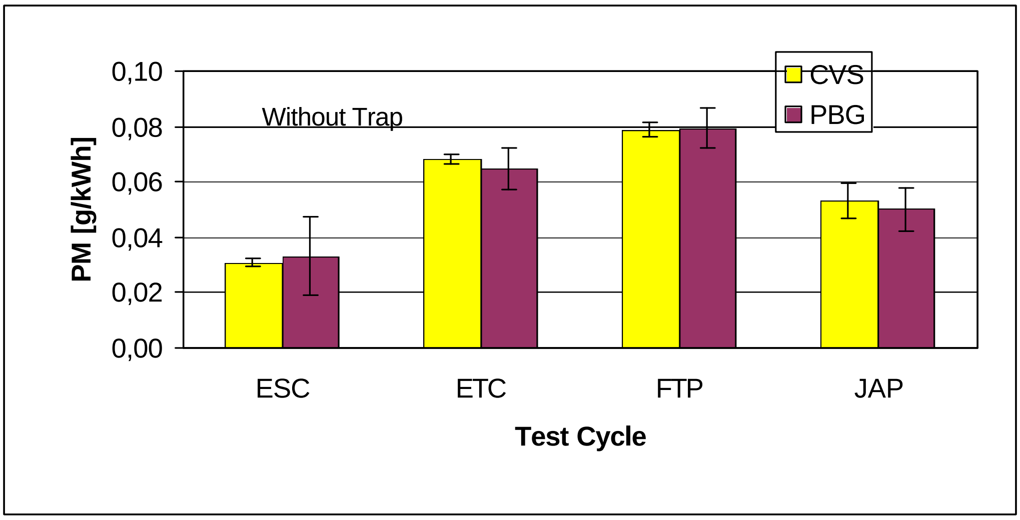

***Figure 10**: Correlation between CVS and Pierburg system*

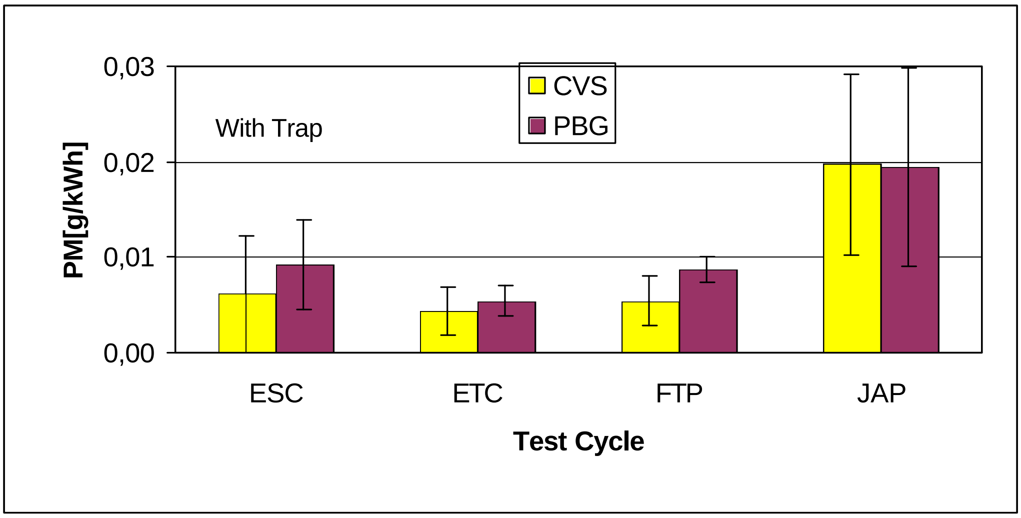

***Figure 11**: Correlation between CVS and Pierburg system with PM trap*

3.5 Measurement Accuracy

Accuracy of exhaust emissions measurement, especially PM measurement, is a crucial issue with regard to future low emission limits. Therefore, accuracy considerations were an important part of the correlation study. To determine PM test-to-test repeatability, it is essential to start with test conditions where engine variability is low. These are modes or test cycles where the PM composition does not change very much and where PM is mainly carbonaceous material. Figure 12 shows that at mode B100 and at ESC the

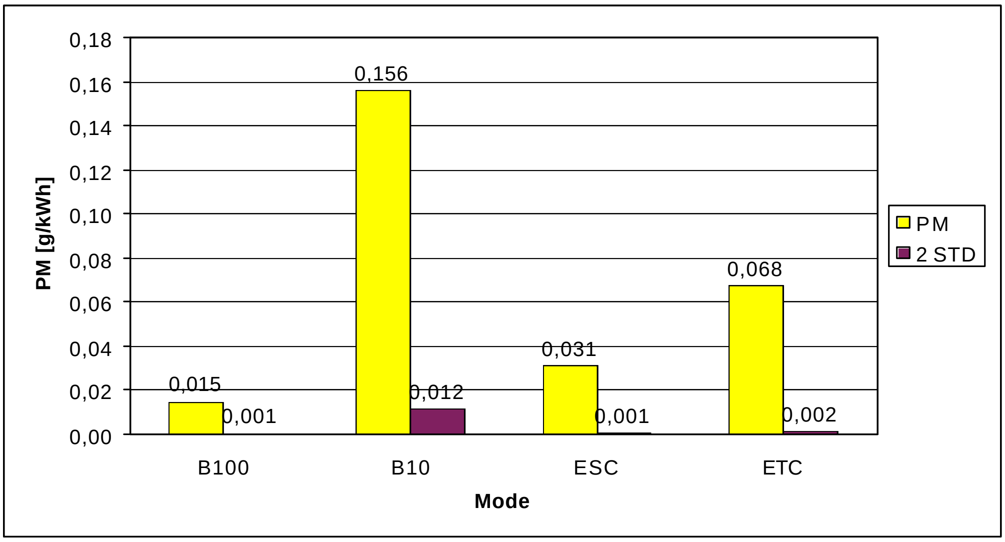

***Figure 12**: PM accuracy results at different modes and test cycles*

absolute standard deviation (2 STD) reached 0.001 g/kWh which is about 20 % of the Euro 4 PM standard. At a low load mode with a higher SOF content the STD increased to 0.012 g/kWh. These results were confirmed in the 7 sample pair correlation study (see figure 13) with the relative variability around or below 10 % in most cases for the tests w/o trap.

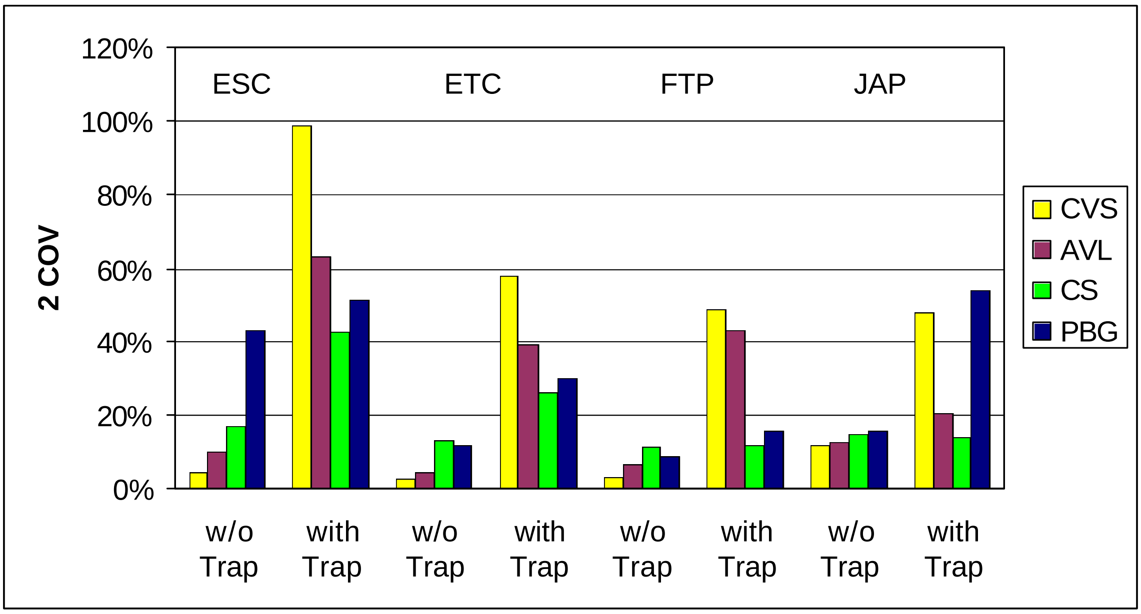

***Figure 13**: PM relative accuracy results at different test cycles*

However, the results became much worse and highly inconsistent between the measurement systems for the tests with trap. As an example, the absolute PM level on the JAP with trap (0.018 g/kWh) was slightly higher than on the B100 mode (0.015 g/kWh), but the STD increased by a factor of 9 to 0.009 g/kWh. The reason for the high variability is believed to be the sulfate content of the particulates. Figure 14 shows that for all tests with PM trap sulfate is the predominant portion of PM. It is well known that sulfate emission is highly variable due to storage and release effects in the trap and in the measurement system.

It can therefore be concluded that the current PM measurement method is sufficiently accurate (10 to 20 %) down to PM levels of 0.01 g/kWh as long as the sulfate emission is negligible. This would require virtually sulfur free fuel with many aftertreatment systems.

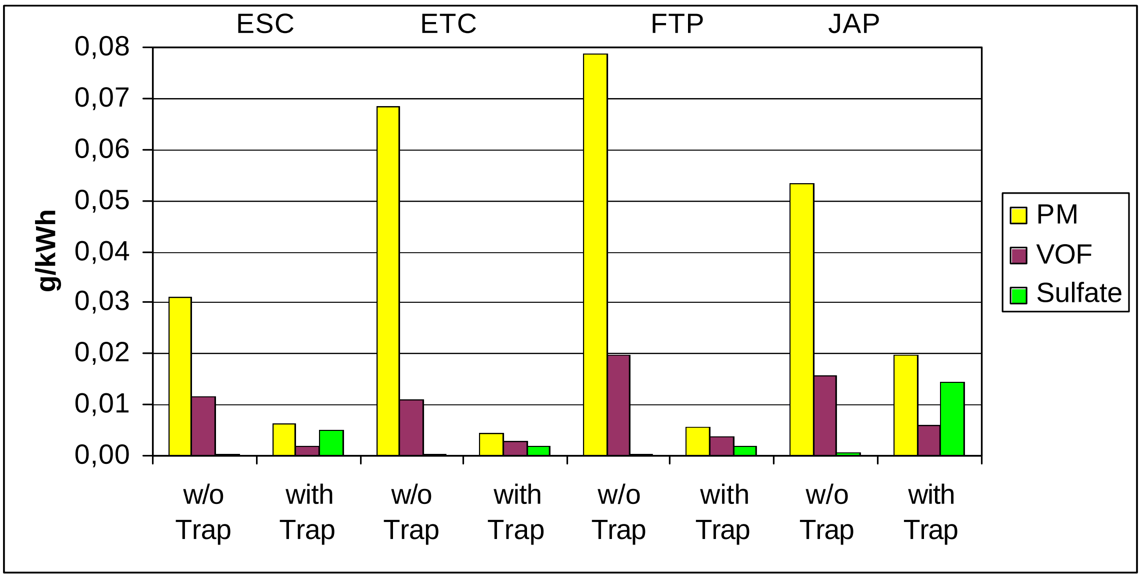

Figure 14*: Comparison of PM composition with and w/o trap*

4 RESULTS OF THE JARI CORRELATION STUDY

The second correlation study was contracted to the Japanese Automotive Research Institute (JARI) and was conducted between September and December 1999 with a 3.9 l, R4, turbocharged IDI engine and a partial flow systems from Horiba. A diesel fuel with 35 ppm sulfur level, low density (826 kg/m³) and normal cetane number (49) was used. The engine had a base PM level of 0.08 g/kWh on the ESC cycle and 0.09 g/kWh on the ETC cycle.

4.1 Transient Operation of Partial Flow Dilution Systems

Like for the EMPA study, the proportionality of the partial flow sample flow was checked by a linear regression between sample probe flow (g/h) and exhaust flow (kg/h) signals. The Horiba system had a very good response to changes of the exhaust flow with a correlation factor of 0.9985.

4.2 Parameter Study

A parameter study similar to the EMPA study was conducted, but with less parameters investigated. The detailed analysis of the parameter study is not yet available. However, over all tests conducted the partial flow system measured about 5% to 20% lower than the CVS system regardless of transient or steady state operation, as shown in figure 15. Together with the good proportionality results presented in chapter 4.1, it is therefore evident that the difference between partial and full flow dilution cannot be attributed to the transient operation.

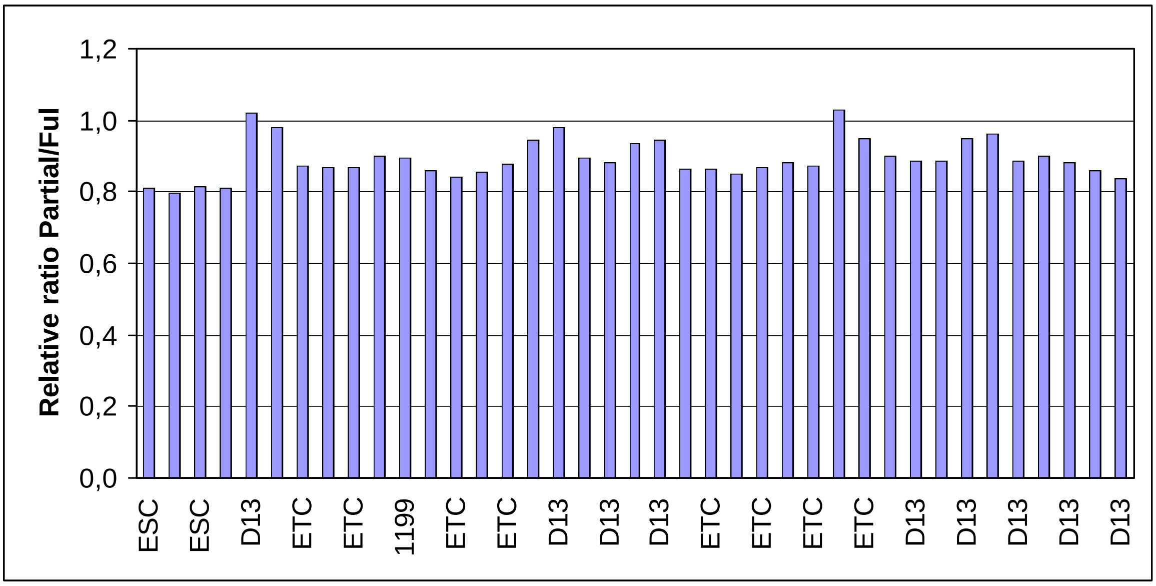

***Figure 15**: Ratio between partial flow and CVS system for different test cycles*

4.3 Correlation Study

As in the EMPA study, the correlation study was conducted on two transient cycles (ETC, US FTP) and two steady state cycles (ESC, Japanese 13-mode cycle) according to the ISO equivalency criterion, i.e. a 7 sample pair comparison between the systems under investigation, and evaluated with a t-test. As shown in table 9, the test was significant for all test cycles indicating a significant difference between the partial and the CVS system.

ESC mode				ETC mode			
TTEST	1,9E-07			TTEST	1,4E-07		
FTEST	5,2E-07	3E-06		FTEST	7,1E-07	2,1E-06	0,00033
Average	0,07529	0,09049	0,8322	Average	0,06563	0,07732	0,8491
STDEV	0,00072	0,00174	0,01352	STDEV	0,00084	0,00146	0,01803
COV %	0,95821	1,92757	1,62473	COV %	1,28569	1,88967	2,12333

FTP mode				J13 mode			
TTEST	4,4E-09			TTEST	2,3E-05		
FTEST	7,1E-06	5,9E-06	0,00045	FTEST	1,6E-06	1,7E-05	0,00266
Average	0,08678	0,09908	0,87602	Average	0,04857	0,05675	0,85909
STDEV	0,00266	0,00243	0,02125	STDEV	0,00128	0,00417	0,05154
COV %	3,06101	2,45699	2,42594	COV %	2,6319	7,35035	5,99981

***Table 9**: Correlation results of the Horiba system*

The results are also shown graphically in figure 16. The error bars represent the test-to-test repeatability based on two standard deviations. There is no overlap of the error bars indicating that the system is not equivalent to the CVS system.

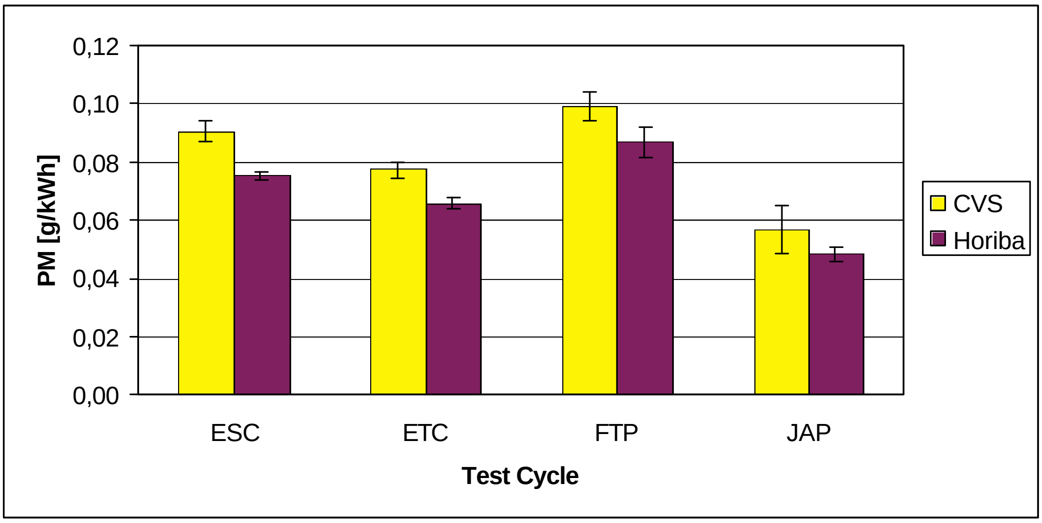

***Figure 16**: Correlation between CVS and Horiba system*

5 RESULTS OF THE RWTUEV CORRELATION STUDY

The third correlation study was contracted to the German technical service RWTUEV and was conducted between December 1999 and May 2000 with a Volvo engine (12 l, R6, TCI, 260 kW) and two partial flow systems from AVL and NOVA. The NOVA system was investigated in the system correlation exercise, only, but not in the parameter study. A city diesel fuel with 20 ppm sulfur level, low density (820 kg/m³) and high cetane number (56) was used. The particulate level of the engine was 0.04 g/kWh on the ESC cycle and 0.06 g/kWh on the ETC cycle.

5.1 Sample Probe Design

The following sampling probes were investigated on ESC and ETC test cycles with 2 repeats on the following test matrix:
Open probe: ESC ETC
Reversed probe: ESC ETC
Hatted probe: ESC ETC ESC ETC
Multi-hole probe: ESC ETC ESC ETC
Open probe: ESC ETC
Reversed probe: ESC ETC

The test program was conducted with the partial flow dilution system compared to the CVS system running at standard conditions. The test results are summarized in table 10.

Test	Number	Open probe	Rev. open probe	Hatted probe	Multihole probe
ESC	1	0,045	0,043	0,043	0,044
ESC	2	0,046	0,043	0,043	0,044
ETC	1	0,059	0,056	0,053	0,052
ETC	2	0,054	0,053	0,053	0,053

***Table 10**: Influence of sample probe design on PM emission*

An ANOVA was conducted as a statistical comparison of the sample probe design for the absolute values and the relative difference to the CVS system. Overall, there was no statistically significant difference between the four probes although the open probe design was closer to the CVS as shown in table 11.

Test	Number	Open probe	Rev. open probe	Hatted probe	Multihole probe
ESC	1	-0,005	-0,007	-0,008	-0,007
ESC	2	-0,005	-0,007	-0,008	-0,010
ETC	1	-0,002	-0,007	-0,009	-0,006
ETC	2	-0,005	-0,006	-0,008	-0,007

***Table 11**: Influence of sample probe design – Difference to CVS*

5.2 Parameter Study

For a better statistical evaluation, a randomized factorial test plan was applied for this part of the program. The goal was the independent variation of dilution ratio, dilution air temperature and sample line temperature and to evaluate their effect on PM mass and composition, which was not possible with the test design of the EMPA program. After considerable discussion in the Working Group WG 2, a full factorial test plan was decided for the above parameters with 3 factors at 2 levels and 1 repeat, as shown in table 12.

A = Dilution ratio (DR):	0 = 4
	1 = 12 for B 100 and B 25; = 8 for ESC and ETC
B = Dilution air temperature (DAT):	0 = 20 °C
	1 = 30 °C
C = Sample line temperature (SLT) :	0 = 150 °C
	1 = 200 °C

	Standard	Run	A	B	C
1	11	1	0	1	0
2	13	2	1	0	0
3	2	3	0	0	1
4	6	4	1	0	1
5	3	5	0	1	0
6	12	6	0	1	1
7	1	7	0	0	0
8	16	8	1	1	1
9	8	9	1	1	1
10	10	10	0	0	1
11	4	11	0	1	1
12	15	12	1	1	0
13	9	13	0	0	0
14	5	14	1	0	0
15	7	15	1	1	0
16	14	16	1	0	1

***Table 12**: Test matrix for parameter study*

The statistical evaluation has not yet been completed, and will therefore not be reported herein.

The test results of the parameter study are summarized in table 13 for the B100 and B25 modes and in table 14 for the ESC and ETC.

B25								
DR	DAT	SLT	PM1	PM2	Mean	Mean DR	Mean DAT	Mean SLT
	20	150	0,066	0,063	0,0645		0,0683	0,0670
4		200	0,069	0,066	0,0675	0,0661		0,0676
	30	150	0,067	0,064	0,0655		0,0664	
		200	0,065	0,069	0,0670			
	20	150	0,071	0,071	0,0710			
12		200	0,067	0,073	0,0700	0,0685		
	30	150	0,067	0,067	0,0670			
		200	0,065	0,067	0,0660			
B100								
DR	DAT	SLT	PM1	PM2	Mean	Mean DR	Mean DAT	Mean SLT
	20	150	0,027	0,028	0,0275		0,0291	0,0290
4		200	0,031	0,031	0,0310	0,0303		0,0303
	30	150	0,032	0,030	0,0310		0,0301	
		200	0,031	0,032	0,0315			
	20	150	0,031	0,030	0,0305			
12		200	0,027	0,028	0,0275	0,0290		
	30	150	0,027	0,027	0,0270			
		200	0,032	0,030	0,0310			

***Table 13**: Test results of parameter study for modes B25 and B100*

ESC								
DR	DAT	SLT	PM1	PM2	Mean	Mean DR	Mean DAT	Mean SLT
	20	150	0,042	0,041	0,0415		0,0439	0,0434
4		200	0,043	0,044	0,0435	0,0431		0,0453
	30	150	0,046	0,042	0,0440		0,0448	
		200	0,042	0,045	0,0435			
	20	150	0,041	0,044	0,0425			
8		200	0,048	0,048	0,0480	0,0455		
	30	150	0,046	0,045	0,0455			
		200	0,047	0,045	0,0460			
ETC								
DR	DAT	SLT	PM1	PM2	Mean	Mean DR	Mean DAT	Mean SLT
	20	150	0,059	0,056	0,0575		0,0585	0,0579
4		200	0,057	0,056	0,0565	0,0563		0,0591
	30	150	0,055	0,053	0,0540		0,0585	
		200	0,056	0,058	0,0570			
	20	150	0,057	0,059	0,0580			
8		200	0,059	0,065	0,0620	0,0608		
	30	150	0,061	0,063	0,0620			
		200	0,060	0,062	0,0610			

***Table 14**: Test results of parameter study for ESC and ETC test cycle*

Whereas the influence of the dilution air temperature and the sample line temperature was only minor, dilution ratio had a slight influence in most cases. Again, it should be noted that the differences in absolute numbers were very small between 0.002 and 0.005 g/kWh. The trend is shown in figure 17 for B25 and B100: for B25, PM is higher at the higher dilution ratio except for the

DAT/SLT combination of 30°C/200°C, whereas for B100, PM is lower at the higher dilution ratio except for the DAT/SLT combination of 20°C/150°C. ESC and ETC trends are shown in figure 18. The results are more consistent with a higher PM at higher dilution ratio under all DAT/SLT combinations.

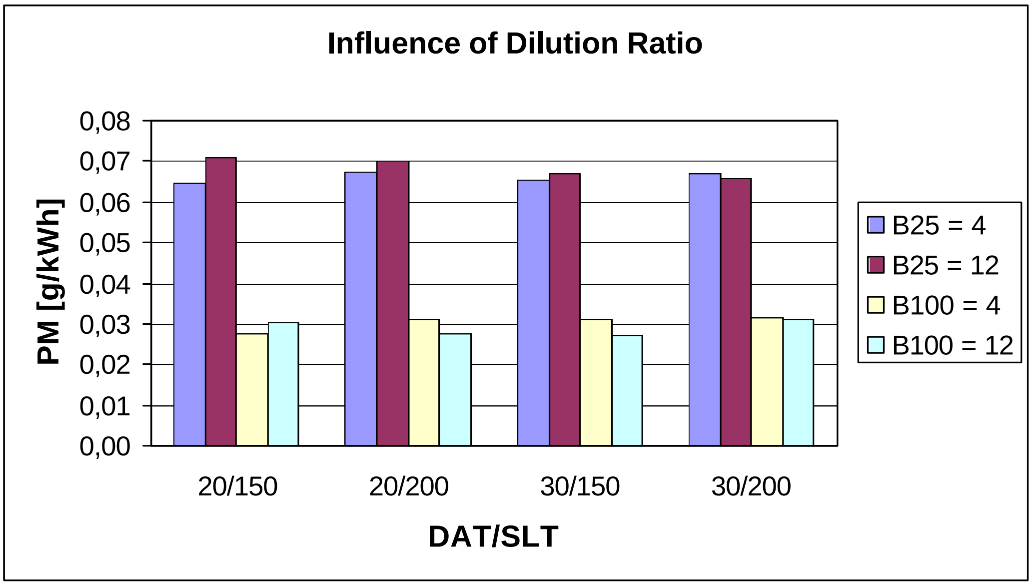

***Figure 17**: Influence of dilution ratio on PM emission (B25 and B100)*

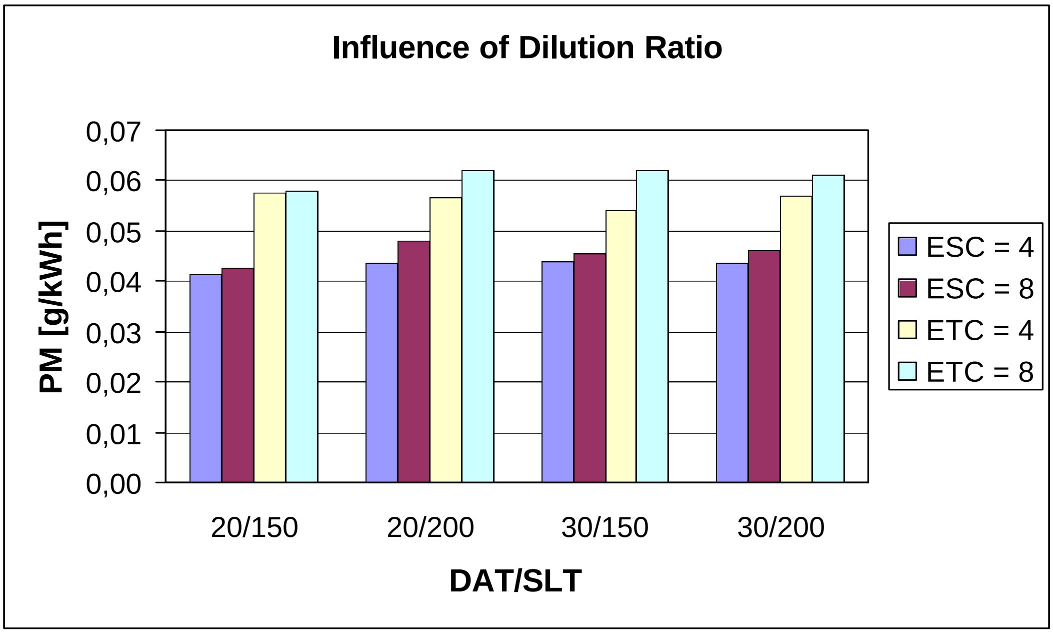

***Figure 18**: Influence of dilution ratio on PM emission (ESC and ETC)*

5.3 Correlation Study

As in the EMPA and JARI studies, the correlation study was conducted on two transient cycles (ETC, US FTP) and two steady state cycles (ESC, Japanese 13-mode cycle) according to the ISO equivalency criterion, i.e. a 7 sample pair comparison between the systems under investigation, and evaluated with a t-test. The candidate partial flow dilution systems were from AVL and NOVA. The results are summarized for the AVL in table 15, and for the NOVA in table 16.

Statistical Data	ESC	ETC	FTP	JAP
Mean, CVS	0,0521	0,0583	0,0939	0,0649
Std. Dev., CVS	0,0020	0,0020	0,0039	0,0016
COV, CVS	3,74%	3,39%	4,19%	2,43%
Sample Size, CVS	7	7	7	7
Mean, AVL	0,0443	0,0559	0,0770	0,0454
Std. Dev., AVL	0,0030	0,0029	0,0048	0,0028
COV, AVL	6,74%	5,11%	6,18%	6,08%
Sample Size, AVL	7	7	7	7
Mean Difference	-0,0079	-0,0024	-0,0169	-0,0194
Relative Difference	-15,07%	-4,17%	-17,96%	-29,96%
F-Test	0,32517	0,39281	0,65482	0,19721
Statistical Conclusion	C=R	C=R	C=R	C=R
T-Test	0,00015	0,08890	0,00001	0,00000
Statistical Conclusion	C<R	C=R	C<R	C<R

***Table 15**: Correlation results of the AVL system*

Statistical Data	ESC	ETC	FTP	JAP
Mean, CVS	0,0521	0,0583	0,0939	0,0649
Std. Dev., CVS	0,0020	0,0020	0,0039	0,0016
COV, CVS	3,74%	3,39%	4,19%	2,43%
Sample Size, CVS	7	7	7	7
Mean, NOVA	0,0477	0,0557	0,0794	0,0571
Std. Dev., NOVA	0,0021	0,0029	0,0079	0,0021
COV, NOVA	4,48%	5,25%	9,99%	3,70%
Sample Size, NOVA	7	7	7	7
Mean Difference	-0,0044	-0,0026	-0,0144	-0,0077
Relative Difference	-8,49%	-4,41%	-15,37%	-11,89%
F-Test	0,83048	0,36133	0,11178	0,48964
Statistical Conclusion	C=R	C=R	C=R	C=R
T-Test	0,00164	0,08151	0,00208	0,00001
Statistical Conclusion	C<R	C=R	C<R	C<R

***Table 16**: Correlation results of the NOVA system*

Except on the ETC cycle, both partial flow systems measured lower than the CVS system on all other cycles. Since the ETC is the cycle with the highest transient operation, the difference cannot be attributed to the transient operation. This has already been observed with the other correlation studies, and needs further investigation. The relatively high disparity of the AVL on the FTP and JAP cycles is partly due to a malfunction of the flow controller at high dilution ratios of 15 to 20, which frequently occur on those low load cycles. The problem was only detected upon completion of the tests, and the results have not been corrected. The results with NOVA are also shown graphically in figure 19. The error bars represent the test-to-test repeatability based on two standard deviations. In all but one case, there is a overlap indicating that the system is close to the CVS system although statistically different.

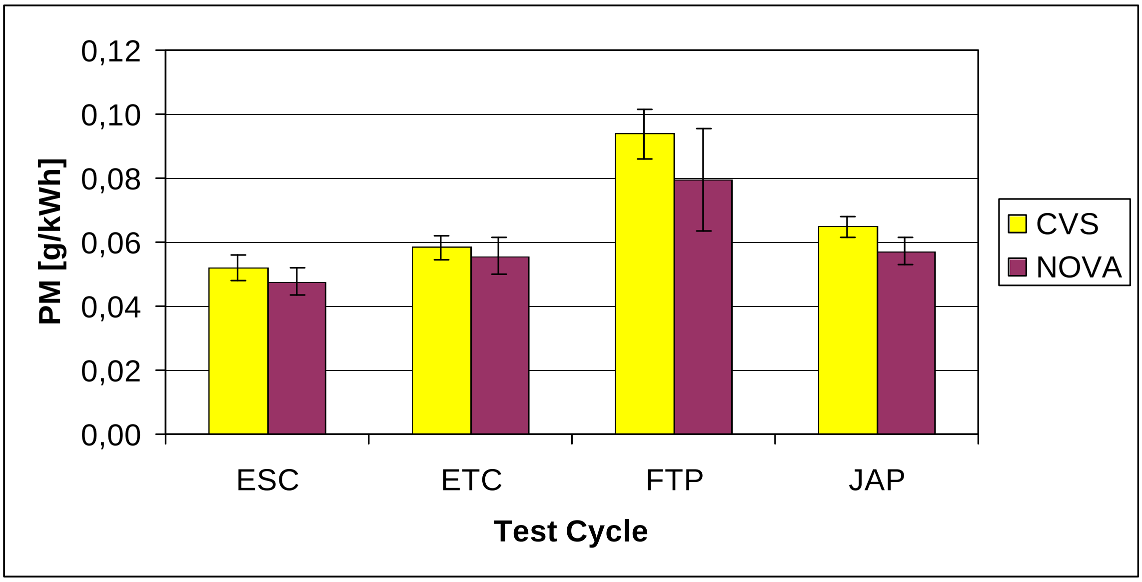

Figure 19*: Correlation between CVS and NOVA system*

5.4 Gaseous Emissions Study

A comparison was conducted between raw and dilute measurement under transient conditions. Two analyzer benches were used on the test cell for parallel measurement of dilute emissions with a CVS system and raw emissions using exhaust mass flow measurement. The calculation procedures were applied in accordance with ISO/WD 16183, and different signal transformation algorithms were compared.

Since CO, NO_x and CO_2 emissions generally do not change in their chemical composition during the dilution process, their measurement values in the raw and dilute exhaust gas should be identical under steady state engine operation. The situation is different for HC emission where, based on previous experience, different measurement values may occur due to changes of the chemical composition during the dilution process. Therefore, the two analyzer systems were first optimized under steady state conditions for best correlation and then run on the ETC and the US FTP.

The results of the correlation between raw and dilute gaseous emissions measurement is shown in figure 20. In general, the difference between the systems was less than 4%, which is considered a very good correlation.

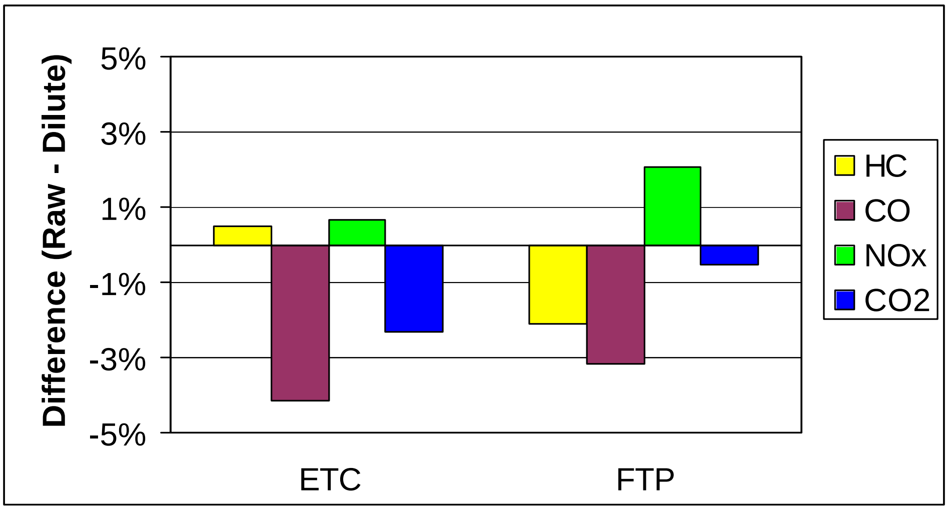

***Figure 20**: Correlation between raw and dilute emissions measurement*

Four different signal transformation algorithms were investigated in the study. Two of them were quite simple delay times (t90, t50), the other two more complex mathematical operations such as forward transformation (f-trans) of the exhaust mass flow signal and backward transformation (z-trans) of the emissions concentration signal. Figure 21 shows that the differences of the algorithms are minor, e.g. within less than 2% for NO_x. Therefore, the easily applicable t50 is proposed for the ISO standard 16183.

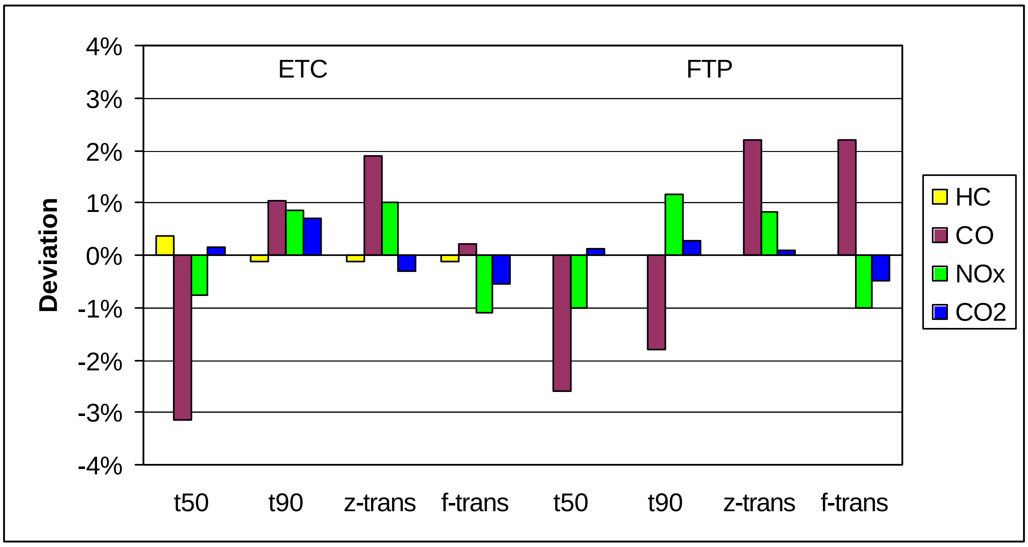

***Figure 21**: Comparison of different calculation algorithms*

6 RESULTS OF THE SWRI CORRELATION STUDY

6.1 Test Matrix

The work at SwRI constitutes the fourth study, which was requested by EPA. It is currently "piggybacked" with another study, underwritten by the US Environmental Agency (USEPA) and the California Air Resources Board (ARB), to develop a transient test cycle for nonroad applications. Contractually, EMA is funding work on the AVL partial flow unit ("SPC-472") while EPA is funding work on a partial flow unit provided by Sierra Instruments,("BG-2"). Recently, a third unit was provided by EPA's testing labs in Ann Arbor. This Horiba "MDLT" was shipped to SwRI and installed, in late October of this year, within a single series of tests performed on the John Deere 6101 engine.

The addition of SwRI was thought to be beneficial to the ISO program for a number of reasons. First it provided another data set, at another facility, to better characterize facility-to-facility variation between two systems that are common to multiple facilities in the program, the AVL, and the CVS. Secondly, it provided an opportunity to acquire correlation data on a broader spectrum of engines, as denoted in table 17. Finally, testing at SwRI would provide a data set on a greater number of transient test cycles (see table 18).

Manufacturer	Model	Power (hp)	Fed Cert	Nonroad	Calif. Cert	ARCO EC
Hatz	IB030	7	**X, ISO**	**X**		
DDC	Series 60	500			**X**	**X, ISO**
Caterpillar	3508	850	**X, ISO**	**X**		**X**
Deere	6101	300		**X**	**X, ISO**	

***Table 17**: Overview of engines, fuels and partial flow systems*

FTP = On-hwy US FTP trans Cycle	EXC = excavator
ETC = On-hwy European trans cycle	CRT = crawler tractor
AGT = ag tractor	RTL = rubber-tired loader 'typical'
AWT = arc welder 'typical'	RTQ = rubber-tired loader 'high torque transient'
AWQ = arc welder 'high torque transient'	SKT = skid-steer loader 'typical'
BHL = backhoe loader	SKQ = skid-steer loader 'high torque transient'

***Table 18**: Candidate transient test cycles*

6.2 Test Results

Testing has been completed on three engines, using three of the partial flow dilution systems, in comparison with the CVS. The Navistar engine was tested with both the AVL and BG-2, the DDC with the AVL only and the Deere with the AVL and Horiba. The test data have not been completely analyzed, so far, and must be recognized as preliminary. Any conclusions from the results can only be drawn after further analysis.

While the Navistar engine showed initial promise with the AVL, its performance with the BG-2 was poor. Additional testing on the other engines, with one or more of the systems, exhibited poor correlation results when compared to the CVS. Particularly disturbing were the poor correlation data, for all the partial flow systems, under steady-state conditions, regardless of the engine being tested. Partial flow systems have generally been adjudged to be consistent, repeatable and have demonstrated good correlation with full flow systems under steady-state conditions. PM disparities averaging between 20 and 30 % and as great at 50% under steady-state conditions, are in contradiction to the results from the three other correlation studies reported herein and to commonly accepted practice in using partial flow systems under steady-state test conditions. The results are summarized in figure 22.

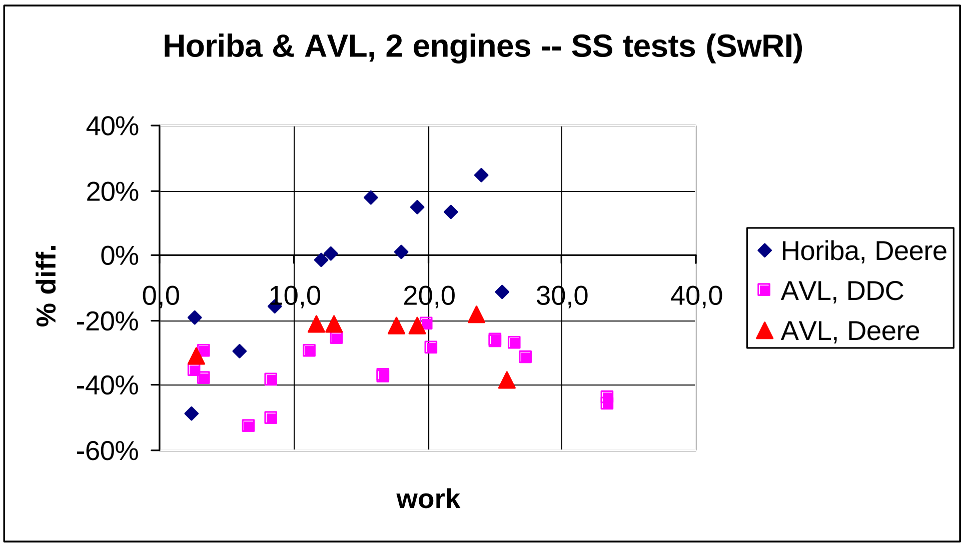

***Figure 22**: Correlation between partial flow and CVS systems under steady state conditions*

Considering these differences, it is not surprising that the correlation results on the transient cycles are poor compared to the other correlation studies. The AVL system, which was also used on the European correlation studies (EMPA, RWTUEV) was tested on three engines. While initial test results on the Navistar engine proved promising with an average difference of -7.9 %, subsequent test results on both the DDC and Deere got worse. While displaying relatively similar consistency as other units at other facilities, i.e. with lower PM values, the disparity (as high as 40% on the DDC at the AGT) has been great, when compared to the CVS. Test results with the Horiba on the Deere engine also yield a poor % difference to the CVS ranging between +10 % and –22 %. A summary of all results is shown in figure 23.

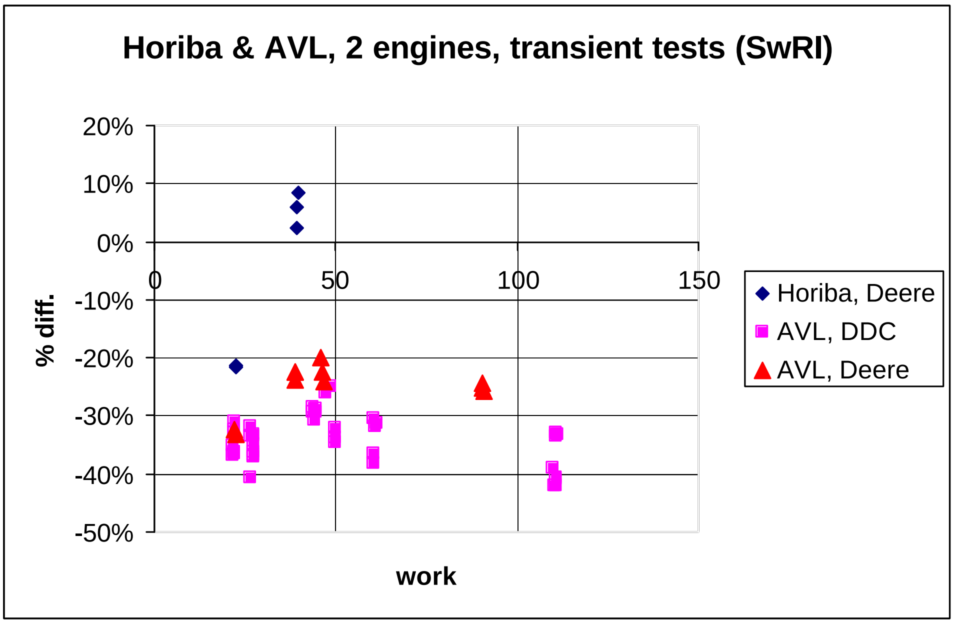

***Figure 23**: Correlation between partial flow and CVS systems under transient conditions*

6.3 Further Procedure

Because of the anomalous test results, even under steady-state conditions, an ad-hoc workgroup, consisting of the instrument manufacturers, SwRI, and representatives from EMA and EPA, has been established to review the data and try and determine the reasons behind the large disparity between partial and full flow correlation and the significant data scatter. In discussions to-date, an explanation of these results still remains unclear. Until an underlying root cause can be determined, further testing has, for the moment, been suspended.

The data analysis will include principally two steps, i.e. identification of any data trends and particulate analysis. Once the results from these two steps are available, the further procedure will be decided. This might also include a dedicated correlation study with a fully formulated work plan.